Modelling for Control:
Combination of Education Approaches

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Abstract: At the University of Ljubljana, Faculty of Electrical Engineering we have introduced several years ago the Bologna study. At the postgraduate or master level, students can choose among eight different possible study fields, where one is Control systems and computer engineering. In the first semester of this study field, all students have to attend the course entitled Modelling methods. As students come from different faculties, their first-level education differs. As a consequence, some additional effort is needed each year to adjust the knowledge, which is very important for all the participants, while new lessons have to be presented in a suitable manner as well. This has to be realized taking into account the available hours for this course and the personal knowledge of all students. The problem was addressed through the combination of different approaches: through the modular organization of the lectures and laboratory exercises, through e-learning extensions, through the development of Matlab toolbox, and through the project-oriented work and exams, which enable additional research activity with the possibility of students' competition participation and/or presentation and publication of research results. Such an organization seems to have significant motivation potential.

Keywords: Modelling, Simulation, Control, Education, Blended Learning, Projects.

1. INTRODUCTION

At the University of Ljubljana, Faculty of Electrical Engineering we have introduced several years ago the Bologna study. Anyone who has completed undergraduate or higher professional study program of the first degree in the amount of at least 180 European credit transfer and accumulation system (ECTS) points in the field of electrical engineering or related mathematical or technical sciences can apply for the postgraduate (i.e. master) level study program. The accepted number of students is defined each year through the entrance exam realized before the start of the winter semester.

The accepted students can choose among eight different study fields, where one of them is entitled Control systems and computer engineering. In the first semester of this study field, all students have to attend the course entitled *Modelling methods*. The main goals of this subject are: to accent the wide and multidisciplinary nature of the area and thus its broad meaning, to describe the typical and also some specific forms of models and their scope, to present advanced knowledge in the field of process modelling, to present some of the software tools and their usefulness in support of the issue being discussed, to acquaint students with the experiments design and their implementation in support to theoretical modelling approaches, to present verification and evaluation in modelling of real systems from technical and non–technical fields, and to acquaint students with appropriate literature selection, research work, and appropriate written and oral presentation of professional, or scientific work results.

As already mentioned, each year a different situation can be expected regarding students' number and their knowledge from the first level of education. While students, which are continuing the study at the University of Ljubljana, Faculty of Electrical Engineering in the field of Control Systems, are familiar with the main concepts of system theory including basics of modelling, simulation and control system design, this is not true for the students from many other faculties (for example from mathematics or physics, and also some others). In some cases, the study at the second level is applied after one or even more years break and some knowledge is forgotten. Although many of the participants have a solid theoretical background in mathematics and physics, each year quite a lot of effort was needed for an efficient start with practical work in the laboratory. It is also important to mention that each year when the semester is finished, our work is evaluated also by students through a questionnaire and so additional problems as well as relative advantages of the education process are estimated continuously. This situation stimulated the investigation of suitable (step by step) education process reorganization where we tried to take into account positively evaluated approaches such as e-learning and flipped-learning (Atanasijević-Kunc et al.,

2011a, Logar et al. 2011, Fita 2015, Hayashi 2015, Willey 2016, Kim and Ahn 2018), project-oriented and collaborative learning (Atanasijević-Kunc et al., 2011a, Logar et al. 2011, Hayashi 2015), combined or blended learning (Kintu et al. 2017, Jayashanka et al. 2018, Kavitha and Jaisingh 2018, Magana et al. 2018, Weerasinghe 2018), the introduction of additional motivation procedures such as students' research work with the possibility of publication or participation in students' competitions, etc. (Matko et al. 2001, Weerasinghe 2018).

Through this paper, the education process organization and reorganization are presented as was realized regarding the course *Modelling methods* in the following way. In the next section, first the expected burden of the education process and intended work forms are described. Through the third section, laboratory hardware and software equipment are presented, while in the fourth section the goals and the efficacy of project-oriented work is discussed. In the fifth section, a software toolbox, which was developed in Matlab, is described. Special attention is devoted to the possibilities, where students can contribute to the development. The responses to animation and visualization demonstration files have motivated further software development as presented in the sixth section. The paper finishes with the concluding remarks and some ideas/plans for future work.

2. EDUCATION PROCESS (RE)ORGANIZATION

The course *Modelling methods* is evaluated with 6 ECTS points. The education process is organized into so-called contact and non-contact hours. Contact hours consist of lectures (three hours per week) and laboratory exercises (two hours per week). In addition, the students are expected to study by theirselves an additional five to seven hours per week throughout the whole semester. Lectures are organized for the whole group of students (around 30), while laboratory exercises are prepared for smaller groups (around 10 students) so that face-to-face communication can be more intensive. Usually, three cycles of laboratory exercises are organized.

Laboratory exercises cannot start at the beginning of a semester because students need to become familiar with a few basic chapters of the subject first. We have therefore decided to reorganize the education process so that through this time lectures are more intensive. The time of one cycle of exercises is used for all who lack knowledge regarding system theory and simulation (students are free to decide to come or not to come to this cycle) while three hours of the other two cycles are used for lectures, but the content is presented in a slightly slower pace to make it easier to follow. In addition, it is also supported by several illustrative examples. When exercises start the lectures' hours are limited as defined by the study plan. It is important to mention that students are invited to come to the laboratory also outside the time scheduled for laboratory exercises.

At the end of the semester, exams are organized. The most usual approach consists of a written part, which is followed (if the result of the written part is positive) by the oral part of the exam. It is important to mention that the final exam mark also depends on the evaluation of the laboratory work. Regarding defined course's goals (for example: to accent the wide and multidisciplinary nature of the area and thus its broad meaning, to acquaint students with appropriate literature selection, research work, and appropriate written and oral presentation of professional, or scientific work results) we have decided to extend the possibilities of exam realization to include also a project work. The structure of the introduced projects is described in all details in section 4.

3. LABORATORY EQUIPMENT

Our Laboratory of Control Systems and Cybernetics has over 50 years long tradition. It is equipped with a number of different pilot plants, which mimic various processes and were chosen to be used for learning and research in the field of modelling, simulation and control-design of dynamical systems. These devices can be divided into different groups taking into account their properties. Some of them are hydraulic devices (rather slow and stable systems), some are pneumatic or combined systems, thermodynamic devices are the slowest. Some electro-mechanical pilot plants are stable while the others are not, however, they are generally the group with rather short time constants. In addition, some pilot plants can operate as multivariable systems (or can be adapted into such operation) while the others are single-input single-output devices. For laboratory exercises of the subject *Modelling methods*, a group of electro-mechanical pilot plants has been chosen as are presented in Fig. 1. Some were produced by professional enterprises, but some of them, like for example the compact inverted pendulum (Bošnak 2016), have been developed in our laboratory so as to extend the number of devices with desired similar properties, which is especially important regarding the goals of education process in *Modelling methods*. These pilot plants are rather fast and enable the realization of several experiments within the block of two hours (weekly burden of exercises), they are very transparent and attractive, all can operate as stable systems. Furthermore, Lagrange equations for theoretical modelling can be used, and of course, some interesting combinations with experimental modelling (including identification and optimization) can be carried out.
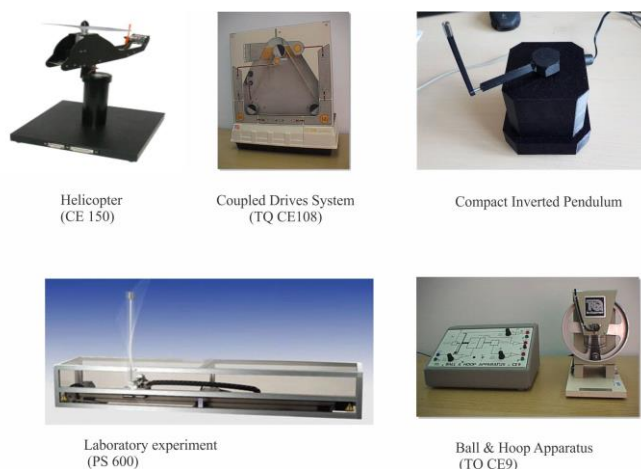

Fig. 1. Electro-mechanical laboratory devices

Each pilot plant is connected to the corresponding personal computer through analog-digital (A/D) and digital-analog (D/A) converters. Each computer features Matlab with corresponding toolboxes, as the majority of students from our as well as other faculties is familiar with the basics of this program. As a consequence, practically no time is needed for learning purposes. It is important to mention that our laboratory has provided a Simulink library extension with a block, which enables the communication with the A/D-D/A converters. In this way, students can experiment with simulation models and with the pilot plants in a similar way, which seems to be very efficient. Therefore, the gap between the theory and practical work has been was narrowed as much as possible. The idea is illustrated in Fig. 2.
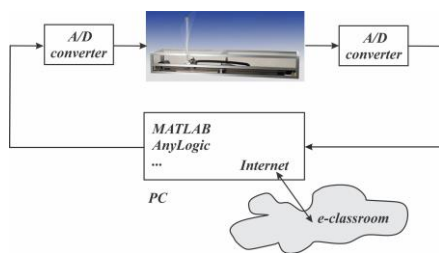

Fig. 2. Working desk with the corresponding equipment

Here we have to mention that in addition to Matlab also the program AnyLogic was installed on each computer and all the computers are online. This means that students have access to the faculty's e-learning environment, where all the needed instructions are also available on-line.

4. PROJECTS DESCRIPTION

One important goal that we have been following from the very beginning is the motivation of students to work online with the aim of passing the exam at the end of the semester. So we have tried to define laboratory work in the form of two rather complex projects where the activities should be enough stimulating, demanding and structured at the same time to enable: the evaluation of laboratory work (obligatory part), the realization of written and oral part of the exam, but also the extensions with which all the participants can also contribute to chosen students' competitions and/or selected conference publications.

Of course, projects were introduced before the start of laboratory exercises. The interesting observation is that all students have (till now) decided for projects instead of the classic way of taking exams. We estimate that this isdue to the following main reasons: I.) Project solving is an interesting and as such also a very motivating activity. As two projects are under investigation, the work is rather demanding and also time-consuming but it seems that this form is well-accepted by a great majority of students. II.) Solving projects is essentially less stressful than usual exams as the quality of the results can be estimated before the work is finished. III.) Students' publications can sometimes be used also as references when applying for different scholarships.

As mentioned, two projects were defined to be solved during the semester. The first is connected with one of the pilot plants. Students of each laboratory cycle are organized into teams of two or three people and they can choose among pilot plants, which are illustrated in Fig. 1. The tasks connected with the first project are the following: development, usage of the theoretical modelling approach, mathematical modelling of nonlinear systems for the control purposes (control design is not the goal, the goal is only the development of a system's model(s)); selection of two operating points and the development of linearized descriptions; design of experiments for the estimation/optimization of the parameters, which cannot be defined through theoretical approach; comparison and evaluation of designed models; a written report of important modelling steps and results; presentation and defence of the developed modelling results together with team colleagues.

The second project is mainly oriented towards non-technical fields and it is introduced and/or supported by two main ideas or approaches: analog systems (elements, variables) and system dynamics, which was developed by prof. Forrester (Forrester J.W., 1961). Through lectures, some important differences and similarities are indicated when comparing methods and results in technical and non-technical areas. In addition, some programs supporting system dynamics modelling approach are presented. Over the last few years, AnyLogic (AnyLogic 2019) has been used when solving the second project.

Regarding the second project, each team has to select a different project topic from the suggested set of possibilities, but they are also encouraged to propose their own ideas for research titles. Typical tasks of the second project are, therefore: selection/proposal of research project taking into account information and data available; selection of influence (important) system variables; development of influence diagram; development of structural diagram; realization of a model in AnyLogic; model parametrization; model evaluation; preparation of a written report in the form of a conference paper; presentation of the developed modelling results together with team colleagues (co-authors).

Some interesting titles that have already been studied are: Modelling the use of public transport and its effect on greenhouse gases, Modelling economic aspects regarding seasonal influenza, Modelling a bitcoin mining process, Modelling the influence of tobacco prices on lung cancer, Modelling a population ageing in Slovenia, Modelling the transition to electric vehicles, Modelling and simulation of suicide rate, Housing policy modelling and simulation, Blue-fin tuna population modelling in western Atlantic, Bark beetle population modelling.

Taking into account our observations and students comments, the following improvements were introduced throughout the last few years:

- The projects are introduced at the very beginning of the semester, instead of at the beginning of the laboratory exercises.

Students have expressed the opinion that it would be better to have the possibility to start with active work on both projects earlier. Our observation regarding this measure is that they do not start to work earlier, but lectures are visited more frequently and questions are posed taking into account also the project tasks.

As two teams (one from each cycle of laboratory exercises) are using the same pilot plant, a competition has been introduced by comparing the modelling results.

• The better team is awarded with additional points and potentially with a higher final mark.

It is evident that students are now more interested also in the results of the other teams and in the advantages which were important through the final result evaluation.

• Additional systematic instructions development regarding typical design steps when a combination of theoretical and experimental modelling is possible.

In spite of the fact that projects were introduced earlier and despite rather strict instructions and theoretical modelling examples, the majority of teams usually needed quite a long time at the beginning of laboratory exercises to design corresponding experiments, which have effectively complemented theoretical modelling results. This has motivated the development of presentations that were included in lectures, but also in the so-called Laboratory of mathematical models (LABI), which is more thoroughly described in section 5. It consists of demonstration files and functions in Matlab and it is organized as a toolbox complementing lectures as well as laboratory exercises.

Each year, additional topics/titles are proposed to students regarding the second project. Additionally, we have introduced:

• The titles, which deal with comparisons of different programs available on the market,

• and some interesting/motivating possibilities regarding the animation and visualization of modelling results.

Some possibilities and ideas are presented in the following two sections.

5. LABI – MATLAB TOOLBOX AND ITS EXTENSIONS

The efficiency of the education process can be improved by carefully selected examples, starting from simple and frequently used elements of more demanding systems. As Matlab was chosen as a software environment supporting the education process regarding the subject *Modelling methods*, many files were developed through the last years for demonstration and illustration purposes. To enable very simple and transparent usage of these files, they were organized into the so-called LABI toolbox, which can be started by simply opening the starting window, which is presented in Fig. 3. The buttons of this window enable the opening of further graphical windows which are related to the chapters presented through the lectures (buttons of the first

two columns), but also some basic information regarding the program Matlab, and corresponding Simulink and Control System Toolbox (CST) is enabled (the buttons of the third column).

Fig. 3. Starting window of LABI toolbox

As analysis is one of the most important, but also one of the most frequently used activities during modelling, simulation, and control-system design, special attention was devoted to the development of corresponding functions, which were prepared for single-input single-output (SISO) as well as for multivariable systems (see Fig. 4). They were arranged into a four-levels toolbox supporting different activities in modelling and control-system design (Atanasijević-Kunc et al. 2011b). It can also be accessed through the starting LABI window as indicated in Fig. 3.

Fig. 4. The first level of the analytical toolbox for SISO systems

When theoretical modelling is followed by simulation, presentation of results is very important. In addition to classic graph interpretation, animation can also be an interesting and motivating aspect. We have prepared many such solutions (using s-functions).

As mentioned before, we have also tried to improve the instructions supporting the transition from theoretical model development to experimentation with the real pilot plant. The example was chosen among the plants that were not used during laboratory exercises as the students need to find their solution by themselves. This purpose was achieved by a hydraulic system, where the first animation was realized using the developed simulation model and later a semi-transparent video clip was added enabling the comparison of operation of both, the model and the real pilot plant. This idea has motivated further activities as presented in section 6.

6. VISUAL INSPECTION AND DATA ANIMATION TOOLBOX

As mentioned, the development of Visual Inspection and Data Animation (VIDA) toolbox was motivated by the goal to enhance the laboratory practice. It is a basic augmented reality program that enables simple 2D animations using signals from Matlab and Simulink and a set of drawing tools. Graphical objects can be animated by connecting chosen dynamic object properties (e.g. position, orientation, width, height, colour) to the data signals from Simulink scheme. In order to connect Simulink signals to VIDA toolbox, a special Simulink block "To VIDA Toolbox" is provided as shown in Fig. 5. This block has only one input to which all signals, which are required for the animation, are routed. These signals can then be accessed in VIDA toolbox and connected to the animation objects.
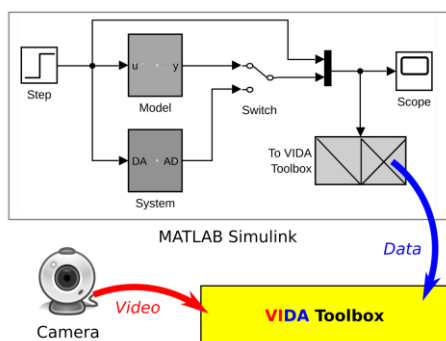
Fig. 5. VIDA toolbox connection with a camera and Simulink

The set of drawing tools enables the generation of basic objects, like points, lines, rectangles, circles and polygons, but also some more complex objects that are common building blocks of electro-mechanical, hydraulic and pneumatic systems are going to be prepared. The user can also define multiple coordinate frames for the canvas on which the objects are presented. Relative poses between the coordinate frames can also be animated. The toolbox also provides some special objects that can be used to track animation trajectories. In spite of the fact that it is limited to 2D problem presentation, VIDA toolbox is complex enough for the illustration of the majority of the pilot plants from our laboratory and also many of the systems that students have modelled in the past.

In Fig. 6 (left part) a simple animation representing a hydraulic system is illustrated, which was created with VIDA toolbox. In this example, the water level in the tank was

animated. Additional features of this toolbox can be used for model verification. For this, a live video stream was obtained from a camera connected to the computer. The animation was then overlaid over the video as it is depicted in Fig. 6 (right part). Therefore, the comparison between real-system performance and the animation can be observed.
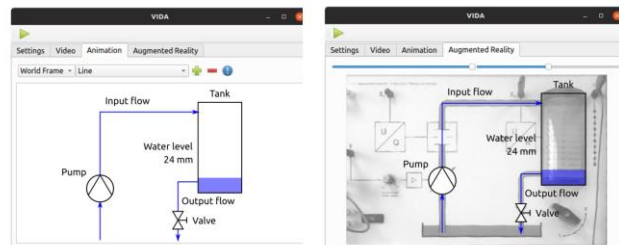

Fig. 6. Animation of a hydraulic system (left) and video stream with animation overlay (right) in VIDA Toolbox

In order to overlay measurements over image frames in the video, the camera needs to be properly calibrated. This can be a daunting challenge that requires careful preparation of the environment. Once the camera is properly calibrated, the augmented reality approach can be used in order to draw virtual objects on top of the real scene. With the use of glasses for virtual or enhanced reality, immersive experience can be achieved. Although this would be an interesting approach, this approach remains in our long-term wish list, since implementation and also usage of such a system for a particular task can be time-consuming even for an experienced user. Therefore, we have constrained ourselves to planar cases. The camera calibration of planar surfaces is simple to achieve with various methods. The VIDA toolbox provides camera calibration tools that enable lens distortion compensation and homography estimation between planar surfaces. For this, a simple four-point calibration procedure is used. The idea is illustrated in Fig. 7.
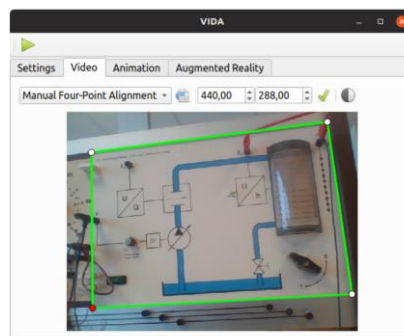

Fig. 7. Camera calibration and animation alignment tool in VIDA Toolbox

The VIDA toolbox can be used during multiple stages of system modelling. In the preparation phase, it can be used to visualize measurements that were obtained using a modelled system. It is possible to animate live sensor data or recorded data from a file. During system modelling, it is useful for visual validation of modelling results.

The toolbox is currently in the active development phase, but the basic features are already tested in laboratory practice.

Currently, the development focus is on tools that will enable recording of the video stream and signals to a file and also playback of the recorded data. In this way, the recorded data could be played and animated in normal, slowed-down and speeded-up time. This will enable additional options for system analysis.

It is important to mention that also the camera itself can be used as a sensor for obtaining system measurements. In view of modelling, vision-based system verification is an interesting and important approach. Machine vision has been very popular in the last years and with the modern computational capabilities of personal computers, this technology has become very accessible. The performance of machine vision approaches can be greatly improved if the environment can be prepared in a suitable way. Object detection can be made very precise and robust if artificial markers are attached to the observed objects. Where proper lightning conditions can be established, methods that rely on object colour can be used, otherwise illumination and geometric invariant pattern tracking is preferred.

Although the list of desired additional features is increasing constantly, we strive towards toolbox simplicity. Since it is a plug and play equipment and it has an intuitive graphical user interface it can be deployed in a matter of minutes. Therefore it enables rapid prototyping and it can be easily incorporated into existing Simulink schemes.

7. CONCLUSIONS

In the first semester of the postgraduate study field Control systems and computer engineering at the University of Ljubljana, Faculty of Electrical Engineering all students have to attend also the course entitled *Modelling methods*. As students are coming from different faculties their first level education differs. As a consequence, some additional effort is needed each year to adjust the knowledge, which is very important for all the participants. In the paper, the combination of different approaches (modular organization of the lectures and laboratory exercises, e-learning extensions, development of Matlab toolboxes, project-oriented work and exams, which enable also additional research activity with the possibility of students' competition participation and/or presentation and publication of research results) is presented by which the education process was improved (is improving) step by step as also the efficacy evaluation of the realized changes is very important. In the near future attention will be devoted to further development of the described VIDA Toolbox. It is important to emphasize that students have accepted the proposed changes very positively, with some minor problems that remain a challenge for our future work.

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